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High-Speed Rail Operations within an Existing Network: An Assessment Model from China

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ABSTRACT

High-speed rail operations have the potential to reduce the long-term decline in rail passenger travel demand for the medium to long distance inter-urban markets. Such decline has been evident through most of the industrialized countries where air and road transport tend to be the dominant modes.

In China, the operations of long distance high-speed rail on fully dedicated track is not very easy to implement, due to the high proportion of passengers who travel between high-speed and conventional railways. An alternative approach would be to allow for mixed operations with trains of various speeds on the same track. This paper puts forward a simulation model designed to allow an evaluation of the most efficient distance for high-speed rail operations under mixed train speed scenarios. The model takes into account the main operating parameters such as passenger volumes, train speeds, capital and maintenance costs, train operating costs and energy consumption. The distance of high-speed train running on conventional rail, that will yield the most economic benefit, can be estimated using the model. The paper shows the results of using the model for a specific example. It is concluded that large-scale high-speed trains have the potential to be successfully operated on conventional rail networks.

Keyword: High-speed railways, Optimization techniques, Train operations; Railway planning.

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INTRODUCTION

Background

High-speed rail operations have the potential to arrest the long-term decline in rail passenger travel demand for the medium to long distance inter-urban markets. Such decline has been evident through most of the industrialized countries where air and road transport have a tendency to be the dominant modes. With the rapid development of high-speed in the last two decades, passenger rail has seen a strong recovery in some countries such as France, Germany and Japan. The advantages of a competitive rail mode for the inter-urban passenger markets are felt both at the individual and the community levels. The benefits are felt in terms of travel time savings, as well as in terms of reduced energy use and environmental impacts, such as noise and air pollution. Such benefits are dependent on the extent that new services can attract mode share away from road and air based travel (Qian,1994 and Zhang, 1993).

High speed operations are usually designed to compete favorably with air transport on price and travel time, given the fact that rail offers a fast city center-to-city center service. High-speed operations may also be competitive with the private car for such inter-urban trips, on the basis of cost and travel time comparisons.

Different countries have developed high-speed railway systems in different ways. Japan has developed an independent high-speed railway system by adopting standard gauge track instead of narrow gauge. High-speed trains (HST) run only on these new purpose built lines (Mochizuki, 1991). In France, HST are allowed to run on the existing railway network. By the end of 1994, the length of commercial service HST on existing lines (3424 km) was more than that on new high-speed lines (2316 km) (SNCF,1995). Several countries have developed tilting trains that operate on conventional lines.

There are unique circumstances in China, in terms of rail demand patterns and network configuration. This has led to the need to evaluate several options on how best to integrate high-speed operations into the existing rail network. Railways in China remain the dominant mode for the medium to long distance transportation markets, for both passengers and freight (Huang, 1997). At the end of 1998, China had 60,000 track kms with track density being much less than that of Japan, UK, France and US (Huang, 1997). The existing rail network has seen major investment with \$US23 billion for the 10 years ending in 1997. In the 5 years from 1998 to 2002 the planned investment is of the order of \$US29 billion. This includes over 5000 kms of new track and 7000 kms of track upgrading (Cao, 1998).

There is currently no rail section which is fully dedicated to passenger trains (a 400 kms. line from Shenyang to Qinghuangdao will be constructed in the near future). Nearly all passenger train movements have to share rail tracks with freight trains.

The Chinese government has proposed to build a new high-speed rail line from Beijing to Shanghai after several feasibility studies. This new 1300 kms double-track line, which is parallel to the conventional line, will be dedicated to passenger operations only.

The existing line will continue to serve the freight rail business and some of the local passenger traffic. There are problems associated with the integration of the high-speed operations into the existing network of services running on conventional tracks at significantly lower speeds. These problems have led to the development of a model to simulate the economic impacts of such integration.

This paper is structured as follows: the next section provides a brief description of the problem being tackled. This is followed by a detailed discussion of the major factors which influence the optimum length of high-speed train operations on conventional lines. The simulation model which was developed to estimate the impacts of varying the high-speed section length is summarised before the results of its application are given.

Problem Specification

The Beijing-Shanghai corridor serves the most important economic region in China. It traverses three municipalities (Beijing, Tianjin and Shanghai) and four provinces (Hebei, Shandong, Anhui and Jiangsu). This represents some 30 percent of the population and almost 47 percent of national GDP (Yang, 1993). The Beijing-Shanghai railway line (BSRL) is also one of the busiest main trunk route in the network. The density of freight and passenger movements has reached three times the average network level. The corridor has a very closely connected with the rest of rail network. Figure 1 shows the relationship between the BSRL and the adjacent network.

Figure 1

The passenger train schedule in 1998 shows 44 and 92 passenger trains running solely and partially on the BSRL, respectively. This means that more than two thirds of passenger trains running on the corridor are connected to the rest of the network. Table 1 shows the daily number of trains using each of the districts of the BSRL, for trains which run solely within the corridor. Table 2 shows the corresponding data for those trains which run only partially on the BSRL.

Table 1

Table 2

In order to establish an express connection from provincial capitals to the municipalities, most of the provinces prefer to have direct through trains. This may lead to the need to maintain through trains after the Beijing-Shanghai high-speed rail becomes operational. This calls for two kinds of passenger trains for those who need to cross both high-speed and conventional sections.

The results of several past studies have shown that the MST should run on BSHSR.

The main reasons are: (a) freight transport volume on Beijing- Shanghai corridor is high and the demand continues to increase. In order to balance the BSHSR and the parallel conventional line, most of the passenger trains should be operated on BSHSR; (b) the maximal operation speed of passenger trains on the conventional network is 160 km/h; and (c) if all passenger trains used high-speed train sets, high capital investment outlays would result.

The model described here will be used to establish the operating scenario with the highest net economic benefit. This will be achieved by comparing the economic impacts of extending HST operations into conventional lines. The problem can be generalized as shown graphically in Figure 2. Referring to Figure 2, the objective is to determine the optimum network coverage to be used for HST operations. That is to say, for a given length of HSR section, an equilibrium point (L_2) can be calculated where the difference of net benefit is minimum (usually zero). Thus it will be easy to judge whether HST is suitable to operate on a given section (including length and volume of passenger flow).

Figure 2

OPTIMAL COVERAGE FOR HST OPERATIONS

General

The decision on the extent to which the HST operation should extend beyond high-speed track, needs to be based on four main types of factors, namely:

(1) Passenger demand pattern

This relates to the origins and destinations of trips served by HST and MST trains. The alternatives to extending HST are (Hu,1998):

- (a) to allow for passenger transfers between the two types of trains. The penalty involved in such transfers, in terms of additional travel time and inconvenience, needs to be traded-off against possible cost savings from mixed speed operations; and
- (b) to increase the number of MST trains operating on the high-speed rail line to allow for through movement of trips.

(2) Operational issues

The timetabling and scheduling issues involved in mixed train/mixed track operations can become critical due to traffic density and line capacity constraints (Mees, 1991; Jovanovic and Harker, 1991 and Higgins et al., 1996a). The potential for delays due to high frequency operations increases under mixed speed operations. The latter requires a strict train hierarchy to be used for train dispatching purposes, Ferreira (1997). The risks of train delays due to unexpected incidents related to track or other problems can be estimated through modeling, Higgins et al. (1996b). Under mixed operations, HST

may need to be given a high degree of priority for train dispatching purposes, thereby relegating MST to low priority status. It is important to ensure that any resultant delays are not borne out by solely by MST operations so as not to penalize trips using such trains.

(3) Infrastructure issues

MST operations in high-speed track require sufficient capacity to avoid potential train conflict related delays. Therefore, there may need to be an increase in the number of passing sidings to allow for overtaking maneuvers (Higgins et al, 1997). In addition, since the requirements for track design standards are different for HST operations, track construction and maintenance costs will need to be allocated between the two types of operations according to damaged caused (Ferreira and Murray, 1997; Zhang et al., 1997; and Martland and Hargrove, 1993).

(4) User benefits and operations related costs

At this stage, the model developed in this research includes the following major costs and benefits (Marchal, 1995):

- (a) changes in patronage levels;
- (b) passenger travel time savings;
- (c) changes in operating revenues;
- (d) train operating costs;
- (e) track and train maintenance costs;
- (f) depreciation changes in investment; and
- (g) energy consumption.

Each of these components will now be discussed in turn.

(a) passenger travel demand changes

When the high-speed line becomes operational, the resultant higher level of service will generate new traffic which is current latent demand. In addition, there will be modal shifts from competing modes such as road and air transport.

Four kinds of passenger flows are identified (Han, 1997):

- N_a^o : Original rail passenger flow transferred from conventional rail;
- N_a^r : Passenger flow transferred from road based transport;
- N_a^a : Passenger flow transferred from air;
- N_a^p : New generated flow.

Where $N_a = N_a^o + N_a^r + N_a^a + N_a^p$, represents total passengers transported by HST.

New generated traffic volume, N_a^p can be calculated by generalized cost model. While modal shift

volume N_a^r, N_a^a can be estimated by a logit type model.

(b) passenger travel time savings

Since the operating speed of HST is much higher than that of MST and road, there will be annual travel time savings, given by:

$$\begin{aligned}
 R_a^t = & N_a^o C_h \left[2L_1 \left(\frac{1}{V_{MST}} - \frac{1}{V_{HST}} \right) - 2L_2 \left(\frac{1}{V'_{MST}} - \frac{1}{V'_{HST}} \right) \right] \\
 & + N_a^r C_h \left[2 \left(\frac{L}{V_{road}} - \frac{L_1}{V_{HST}} - \frac{L_2}{V'_{HST}} \right) + (t_{road}^{access} - t_{HST}^{access}) \right] \\
 & + N_a^a C_h \left[2 \left(\frac{L}{V_{air}} - \frac{L_1}{V_{HST}} - \frac{L_2}{V'_{HST}} \right) + (t_{air}^{access} - t_{HST}^{access}) \right]
 \end{aligned} \tag{1}$$

Where: R_a^t is annual travel time savings due to HST;

C_h is hourly time value (Mao, 1997);

L_1, L_2 are length of sections on high-speed and on conventional rail, respectively;

V_{HST}, V'_{HST} are HST speeds on high-speed and on conventional rail, respectively;

V_{MST}, V'_{MST} are MST speeds on high-speed and on conventional rail, respectively;

L is total length of section concerned ($L = L_1 + L_2$);

V_{road}, V_{air} are road and air travel speeds, respectively;

$t_{road}^{access}, t_{HST}^{access}, t_{air}^{access}$ are access time by road, train and air at origin and destination.

It should be noted that the total door-to-door travel time by air might be more than by HST because of the time taken to access the airports at both ends of the trip.

(c) changes in operating revenues

There will be additional revenue from HST operations. Because the latter offers a higher quality service, it will attract additional passengers if the price is constant. This can be calculated by :

$$R_a^p = 2L(N_a^r + N_a^a + N_a^p)r_{MST} \quad (2)$$

However, if we assume that the volume of traffic does not change, a higher price for HST can be expected. The additional revenue is given by :

$$R_a^p = 2LN_a^o(r_{HST} - r_{MST}) \quad (3)$$

Where: R_a^p is additional income;

r_{HST} , r_{MST} are fares per passenger-km for HST and MST, respectively.

In our study, the revenues are calculated using equation (2).

(d) changes in train crew costs

The train crew costs under HST operations will be different due to the differential in speeds and the difference in total train movements required to service a given level of demand under the two scenarios. Crew cost changes is given by:

$$\begin{aligned} E_c &= (D_c^{MST} - D_c^{HST}) \\ &= \frac{\varepsilon \cdot P_{MST}}{L} \left(\frac{L_1}{V_{MST}} + \frac{L_2}{V_{MST}} \right) \cdot \sum_{MST} NL - \frac{\varepsilon \cdot P_{HST}}{L} \left(\frac{L_1}{V_{HST}} + \frac{L_2}{V_{HST}} \right) \cdot \sum_{HST} NL \end{aligned} \quad (4)$$

Where:

E_c is annual savings in crew costs under HST operations;

D_c^{HST} , D_c^{MST} are annual crew costs for HST and MST, respectively;

P_{HST} , P_{MST} are hourly crew salaries for HST and MST, respectively;

ε is a coefficient related to indirect crew salary on-costs;

$\sum_{MST} NL$, $\sum_{HST} NL$ are train-kilometers achieved in a year by all MST and HST, respectively.

Annual train-kilometers can be calculated according to passenger volume, capacity of a train and its utilization ratio, as set out in equation (5) and (6).

$$\sum_{MST} NL = 2L \cdot 365 \cdot n_{MST} = 2L \cdot \frac{N_a^o}{a_{MST} \cdot \alpha_{MST}} \quad (5)$$

$$\sum_{HST} NL = 2L \cdot 365 \cdot n_{HST} = 2L \cdot \frac{N_a^o + N_a^r + N_a^a + N_a^p}{a_{HST} \cdot \alpha_{HST}} \quad (6)$$

Where: n_{MST}, n_{HST} are number of daily MST trains and HST trains;

a_{MST}, a_{HST} are capacity of MST and HST.

$\alpha_{MST}, \alpha_{HST}$ are utilization ratio of MST and HST.

(e) changes in track and train maintenance costs

Maintenance cost is made up of rollingstock and track (this refers to track structures, power supply and train control equipment). In general, the rollingstock unit maintenance cost of HST is higher than that of MST, due to the types of materials. The unit track related maintenance cost for HST will differ from MST operation due to differences in axle loads, speeds and maintenance standards required. The change in total maintenance cost of HST compared with MST can be expressed as:

$$D_m^e = \sum_i (D_m^{MST} - D_m^{HST}) = \sum_i (D_{mr}^{MST} - D_{mr}^{HST}) + (D_{mf}^{MST} - D_{mf}^{HST}) \quad (7)$$

Where: D_m^e is annual saving in maintenance cost of HST compared with MST;

D_m^{HST}, D_m^{MST} are annual maintenance cost of HST and MST, respectively;

$D_{mr}^{HST}, D_{mr}^{MST}$ are annual maintenance costs of HST and MST for rolling stock, respectively;

$D_{mf}^{HST}, D_{mf}^{MST}$ are annual track maintenance costs of HST and MST, respectively.

The calculation of the annual maintenance cost requires considerable basic data, such as life period of major equipment with the estimation of some of the parameters being quite difficult in practice.

(f) Depreciation changes in capital investment

We consider here only the different investment for the two alternatives. In order to

transport the same passenger volume under HST mode, we need additional high-speed trains due to the capacity of HST (1000 seats/train) being smaller than that of MST (1500 seats/train). Moreover, HST should transport an additional volume of passengers. So the train-sets needed of HST may be higher than that of MST, though the higher speed for HST could reduce requirements. The maximum number of train-set of HST needed in operation can be estimated by:

$$\begin{aligned} q_M^{HST} &= \frac{1}{24} \left[\frac{2L_1}{V_{HST}} + \frac{2L_2}{V_{HST}} + t_{HST}' + t_{HST}'' \right] \cdot \frac{N_a'}{a_{HST} \cdot \alpha_{HST}} \\ q_M^{MST} &= \frac{1}{24} \left[\frac{2L_1}{V_{MST}} + \frac{2L_2}{V_{MST}} + t_{MST}' + t_{MST}'' \right] \cdot \frac{N_a''}{a_{MST} \cdot \alpha_{MST}} \end{aligned} \quad (8)$$

In which t', t'' represent stopping time at the two terminal stations; N_a' is the passenger volume of a day during peak time at HST mode; and N_a'' is the passenger volume of a day during peak time at MST mode.

Usually, the investment of rollingstock under the HST mode will be higher because of the higher cost of train-sets. On the other hand, it is also necessary to equip conventional lines for HST operation. Hence, the depreciation change in investment is given by:

$$E_i = E_{ir} - E_{if} = (D_{ir}^{TVM} - D_{ir}^{TGV}) - E_{if} = \frac{S^{MST} q_M^{MST} \rho}{X_L^{MST}} - \frac{S^{HST} q_M^{HST} \rho}{X_L^{HST}} - \frac{\Delta S''}{X_{L_1}} \quad (6)$$

Where:

E_i is total annual saving in depreciation of investment;

E_{ir} , E_{if} are annual investment saving in rolling stock and track, respectively;

S^{HST} , S^{MST} are purchasing cost for a HST or a MST train-set, respectively;

$\Delta S''$ is additional investment in infrastructure for HST operation on conventional lines.

X_L^{HST} , X_L^{MST} are life periods of HST and MST, respectively;

X_{L_1} is life period of rail track, (Hajime, 1999);

q_M^{HST} , q_M^{MST} are life periods of HST and MST, respectively; and

$\rho = 1 + r$, r represents the percentage of reserved train-sets.

(g) energy consumption

In general, the unit energy consumption of a train varies with its speed. An optimal operating speed exists for a train under given conditions. The saving in energy consumption can be estimated by:

$$E_e = (D_e^{TVM} - D_e^{TGV})^{(1)} + (D_e^{TVM} - D_e^{TGV})^{(2)} \quad (8)$$

$$D_e = \left(\frac{F_m \theta}{\eta} + \frac{\Delta \theta}{V_m} \left(\frac{1 - \delta}{\delta} \right) \right) \sum NL$$

Where:

E_e is annual cost saving in energy consumption;

D_e is annual cost of energy consumption;

(1), (2) represent indices of high-speed and conventional lines, respectively;

F_m is energy consumption per kilometer;

θ is the unit cost of energy;

η is efficiency of energy output;

Δ is auxiliary consumption of energy during the station stop time in an hour;

δ is the coefficient of stop time during travel (ratio of stopping time to total travel time);

V_m is average speed; and

$\sum NL$ is annual train-kilometers produced in operation.

When each parameter in equation (8) is obtained for HST and MST, the saving of energy can be estimated.

THE OPTIMAL NETWORK COVERAGE FOR HST OPERATIONS

The following model can be used to estimate the optimal network coverage for HST operations on conventional lines:

$$f(L_1, L_2) = \text{Max}(R_a^t + R_a^p + E_m + E_i + E_c + E_e) \quad (9)$$

Where:

L_1, L_2 are lengths of section on high-speed and conventional line respectively;

R_a^t is annual travel time saving brought about by HST operations;

R_a^p is the additional revenue from HST operations;

E_m, E_i, E_c, E_e are savings in annual costs of maintenance, investment, crew and energy consumption between HST and MST.

It is difficult to optimize directly L_1 and L_2 by differentiation since numerous factors influence those optimal distances. Hence a simulation model has been developed to calculate an approximate result in practice. This simulation model can be used to estimate the near-optimal distance of HST on conventional railway sections. The procedure is as follows:

- (a) determine the basic parameters such as price of MST, salary of a crew, capacity of a HST and MST and the indices concerning maintenance, investment, and consumption etc.
- (b) select a section on high speed rail line with distances L_1 .
- (c) calculate the coverage of HST operations on conventional rail under different distance and passenger demand.
- (d) find the optimal distance range L_2 , which permits HST to run on conventional rail network and yields a better financial result than MST.

Table 3 shows the results of applying the simulation model in an example when the length of high-speed rail is assumed to be 1300 kms and 800 kms.

Table 3

In Table 3, The results show the way in which the ratio, $L_2/(L_2+L_1)$ varies with passenger flow, rate of occupation in HST and MST, and the distance L_1 . In general, the ratio of $L_2/(L_2+L_1)$ increases gradually with passenger volume. However, this ratio

decreases sharply when the rate of occupation in HST operation is reduced. This is due to an increase in the number of high-speed trains. On the other hand, when the rate of occupation of MST decreases sharply, it causes the ratio of $L_2/(L_2+L_1)$ to quickly increase. This is due to the increase in the number of MST train-sets which translates into an increase in net savings.

It can be seen from Table 3 that the section length on high-speed line, L_1 , has little influence on the ratio of $L_2/(L_2+L_1)$. Figure 3 shows the ratio of $L_2/(L_2+L_1)$ for two different values of L_1 . It should be noted that the benefit savings will drop significantly when passenger volumes increase to about 300 000 persons per year. This is due to additional new train sets needed for HST operation.

Figure 3

Another practical function of the model is to estimate the more efficient operating mode, for a given level of demand and specified L_1 and L_2 values. For example, assuming a forecast passenger flow between Beijing (station B) and Hangzhou (station h) of 300 000 person in a specific year, the distance from Beijing to Shanghai is 1300 km and from Shanghai to Hangzhou is 201 km. Then the favored operation mode will be HST, as shown in Table 4.

Table 4

A detailed operating plan could be scheduled using the above analysis method.

CONCLUSIONS

This paper discussed the methodology to calculate the optimal coverage of high speed trains on conventional track. Based on this analysis, a simulation model has been developed in order to estimate the optimal coverage of high speed trains.

The model described in this paper can be used in practice to determinate the extent to which high speed train operations on conventional rail lines are economically feasible. The results may also be used to help with the task of train planning and scheduling.

In the case of operations such as those encountered in China, with an expensive existing conventional network, it is critical that high speed train operations can be efficiently and effectively integrated into such a network.

In this model, only two operating modes were compared. In order to improve the applicability of the model, it is necessary to add a third mode, i.e. passengers transferring from one type of operation to another. In addition, some of the parameters used to calculate the ratio of L_2/L_1 need to be estimated for the specific circumstances being investigated.

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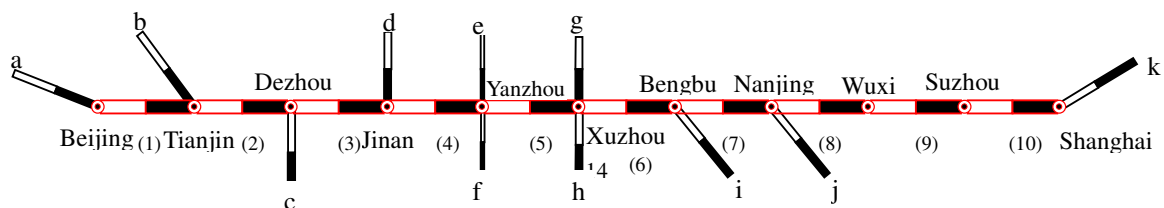
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Legend

Table 1 Number of daily trains running solely on BSRL in each district

District ⁽¹⁾ From	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Beijing ⁽²⁾	15	9	9	7	7	6	6	4	4	3
Tianjin		6	2	2	2	2	2	1	1	1
Dezhou			1							
Jinan				2	2	1	1	1	1	1
Yanzhou					2					
Xuzhou										
Bengbu							1			
Nanjing								12	10	9
Wuxi									4	4
Suzhou										1
Shanghai										
Density ⁽³⁾	15	15	12	11	13	9	10	18	20	19

Note: (1) Districts refer to Figure 1;

(2) First line indicates number of daily trains from Original point, Beijing, passing each district;

(3) Density refers to the number of daily trains passing a district.

Table 2 Number of daily trains running to BSRL from other rail lines

District From	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Beijing	27	8	8	5	4	4	3	3	3	3
Tianjin		18	11	7	7	5	5	5	5	5
Dezhou			3	1	1	1	1	1	1	1
Jinan				11	8	3	3	2	2	2
Yanzhou					1					
Xuzhou						15	14	10	9	9
Bengbu							9	8	8	8
Nanjing								5	5	5
Wuxi									2	2
Shanghai										1
Suzhou										
Density	27	26	22	24	21	28	35	34	35	36

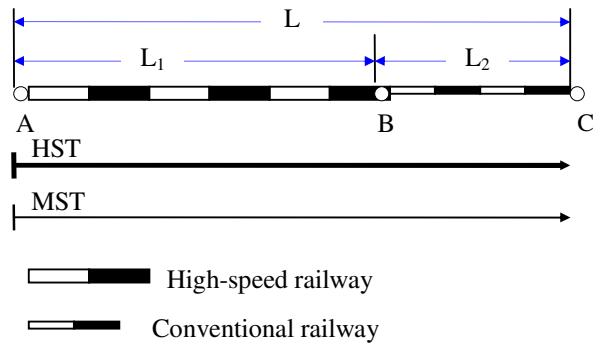


Figure 2 Illustration of mixed railway system

Table 3. Relationship between L_1 , L_2 and related factors

Annual Passenger volume (1000's /year)	146	183	219	256	292	329	365	438	511	584
Distance on HSR	L ₁ =1300 kms									
Distance on CRL (L_2)	463	752	1034	1185	1392	582	711	1180	2307	2865
L_2/L_1 (%)	36	58	80	91	107	45	55	91	177	220
Rate of occupation in HST	40	50	60	70	80	45	50	60	70	80
Rate of occupation in MST	22	29	35	42	48	51	57	71	43	50
Annual Passenger volume (1000's /year)	146	183	219	256	292	329	365	438	511	584
Distance on HSR	L ₁ =800 kms									
Distance on CRL (L_2)	298	365	563	744	923	298	324	664	1423	1791
L_2/L_1 (%)	37	46	70	93	115	37	41	83	178	224
Rate of occupation in HST	40	50	60	70	80	45	50	60	70	80
Rate of occupation in MST	22	28	34	41	48	49	55	70	43	50

Note: L_1 , L_2 is length of sections on high speed and conventional line

Rate of occupation means percentage of average number of passengers to seating capacity in a train.

**Figure 3 Relationship between
passenger flow and distance ratio**

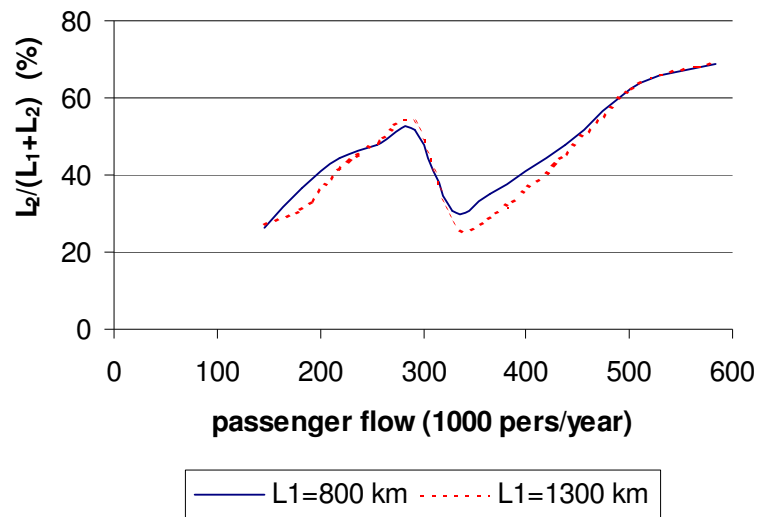


Table 4. Model application in judging favorable operation mode

Original (on HSR)	Destination (on CR)	L ₁ (km)	L ₂ (km)	Traffic (pers/year)	Savings of net benefit (million yuan/year)	Proposed operation mode
B	h	1300	201	300,000	3.22	HST
A	e	800	250	250,000	12.83	HST
C	e	400	250	310,000	-8.96	MST
J	q	1170	400	50,000	-13.76	MST